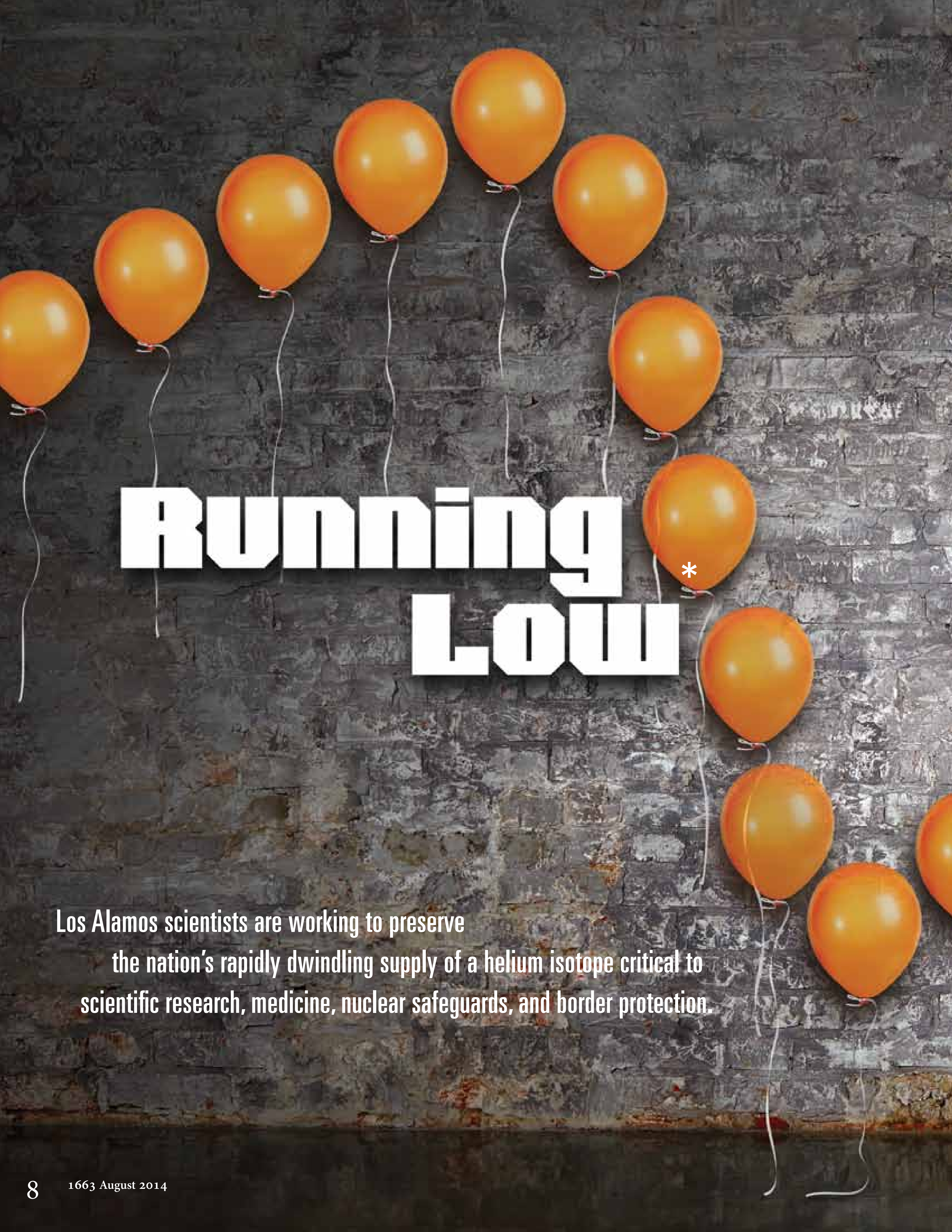


Running Low*

Los Alamos scientists are working to preserve the nation's rapidly dwindling supply of a helium isotope critical to scientific research, medicine, nuclear safeguards, and border protection.

NUCLEAR WEAPONS OFFER MORE THAN JUST DESTRUCTION. They also produce, from the slow decay of hydrogen-3 (also called tritium), a rare isotope of helium the world needs for a number of peaceful purposes. Helium-3, which amounts to only 0.0001 percent of all helium found on Earth, is used in cryogenics, laser physics, and fusion energy research. It is also used in medical imaging of the lungs and in geological exploration around oil and gas wells. Yet more than three quarters of the demand for this byproduct of nuclear weapons production comes from detection systems that safeguard national borders and the international community against the clandestine diversion of nuclear material for violent purposes.

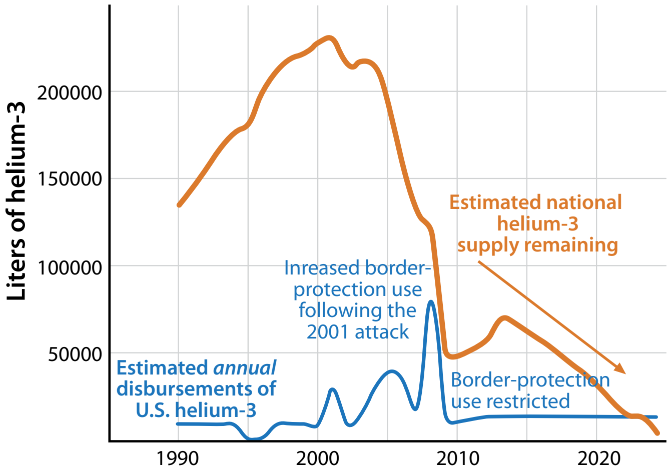
Helium-3 is stable, but its weapons-worthy precursor, tritium, is radioactive and decays into helium-3 with a half-life of 12 years. So when a nuclear bomb's tritium has decayed to the point where it's no longer viable for the operation of the weapon, or when the weapon is retired altogether, the accumulated helium-3 is harvested. Scientists at home and abroad have come to rely on this U.S. supply of helium-3, which today faces an escalating shortage.

In the mid-to-late 1900s, when nuclear weapons production was booming (no pun intended), correspondingly plentiful helium-3 production followed. But then the Cold War began to thaw, and the name of the game slowly shifted from competitive stockpile expansion to cooperative stockpile reduction. For a time, the decline in helium-3 production associated with refurbishing weapons was offset by an increase from dismantling weapons. But with the drawdown in the nation's stockpile leveling off, the U.S. helium-3 supply can no longer keep up with demand. According to the U.S. Department of Energy, about 8000 liters per year are harvested from decaying tritium in weapons, while the annual domestic demand is projected to range between just under 10,000 liters and 14,000 liters, even after significant measures have been taken to mitigate it. Combined international users need even larger amounts. Short of finding an alternative source of helium-3—an uncertain prospect at best—that deficit can only be met at the expense of depleting current reserves. Fortunately, something is being done to stem the demand.

Supply and demand

The problem isn't only the diminishing supply of nuclear weapons. Part of the shortfall comes from an explosion in demand that followed the September 11, 2001 terrorist attacks, when the United States launched an aggressive program to deploy nuclear detectors to border locations and ports of entry. These detectors rely on helium-3 gas tubes to register the presence of fissionable nuclear materials like plutonium by absorbing the neutrons emitted by the material. In 2008, at the height of the expanded production of neutron detectors for the nation's entry points, helium-3 demand soared to nearly 80,000 liters.

* Helium shortages can be a real downer, and the world currently faces two of them. The better known shortage, with its price spikes and shortfalls affecting many industries (including party balloons), primarily concerns helium-4, the most abundant helium isotope in nature. Less well known, however, is a more severe shortage of the much rarer isotope helium-3. Essential for key scientific, medical, and national security applications, no one would dream of filling a balloon with it.



The U.S. supply of helium-3 (orange) has been precipitously declining since the terrorist attacks of 2001. Demand has varied by year, and annual disbursements (blue) have been slashed to extend the life of the national stockpile. But even with these usage restrictions in place, current projections indicate that there will be insufficient helium-3 to meet national needs by the early 2020s and thereafter. (International demand not is shown.)

That something had to be done to protect the rapidly diminishing supply of helium-3 did not escape the U.S. government's notice, and in 2010, Congress began to hold hearings on the problem. It soon decided to stop allocating helium-3 to border protection systems, thereby cutting the demand for it and extending the life of current reserves. This brought down the annual projected demand from over 40,000 liters, according to the White House Office of Science and Technology Policy, to where it currently resides at an estimated 10,000–14,000 liters. Even so, meeting the remaining demand for non-border nuclear detectors and other scientific, medical, and industrial applications continues to overspend national helium-3 reserves, albeit at a slower rate than during the previous decade.

"Something has to give," says Howard Menlove of Los Alamos's Nuclear Safeguards Group. "Either a significant new source of helium-3 must materialize in a hurry, or we must develop an alternative to helium-3 in neutron detectors." Such detectors remain, by far, the isotope's largest-use application (even when border monitoring is removed from consideration), as other, non-border nuclear safeguards activities continue unabated. For example, the International Atomic Energy Agency (IAEA), an independent body concerned in part with nuclear safeguards and ensuring nonproliferation treaty compliance, relies on helium-3-based detectors to conduct nuclear-plant inspections and report its findings to the United Nations. Los Alamos regularly contributes to the training of IAEA inspectors and last year hosted a workshop on helium-3 alternatives that included representatives from the IAEA and others from the international nuclear safeguards community.

"The IAEA has a wide variety of ways to keep track of nuclear materials," says Menlove. "They have tamper-proof cameras and sensor systems installed at nuclear plants around the world. But the main way they account for these high-grade materials is by mass, and that means physically going to the plant with a sensitive detector and comparing weights and neutron emissions from plutonium canisters, one by one.

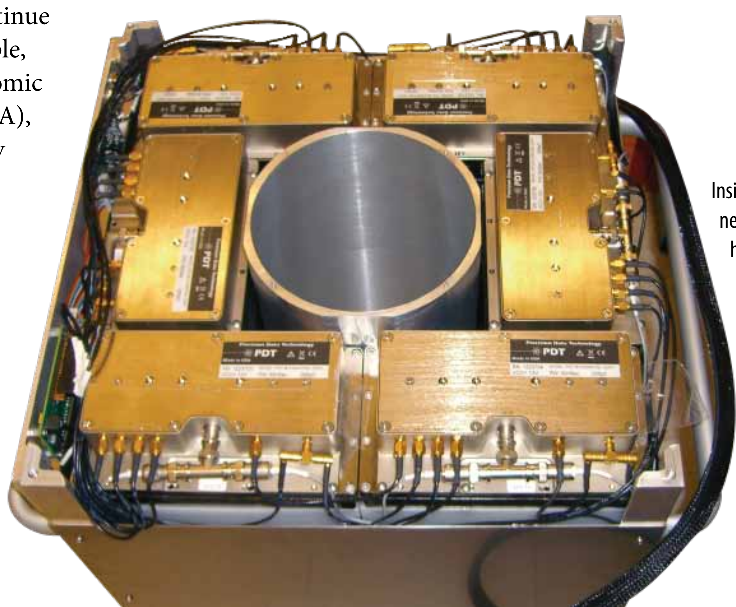
"Until now," he adds, "that has required helium-3."

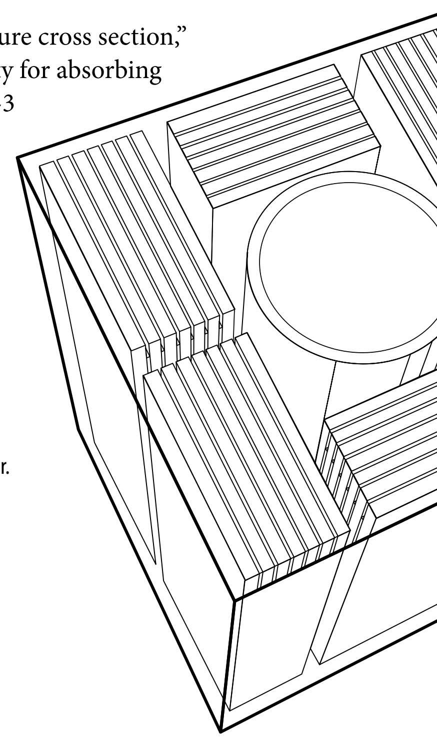
Where there's a will

Replacing helium-3 in neutron detectors is harder than it sounds. Scientists at Los Alamos and elsewhere have been searching for decades to find alternative neutron detection technologies. Other neutron absorbers were studied and prototype systems were developed, yet none fully made the grade. Some prototypes weren't efficient enough; too many neutrons went undetected. Others were too sensitive to gamma rays, which can be mistaken for neutrons and bias the measurement results. Still others were unstable, lacking consistent performance over time. Precious few were even deemed worthy of building to full scale for the purpose of further experimentation because detectors based on helium-3 gas tubes were always better. Now, however, the need for a viable alternative is considerably more urgent.

Daniela Henzlova, a colleague of Menlove's, is part of the renewed effort at Los Alamos to develop a practical non-helium neutron detector. She is keenly aware of why helium-3 is so hard to beat.

"It's got a very high neutron-capture cross section," says Henzlova, referring to its proclivity for absorbing neutrons. "Detectors based on helium-3 represent a mature and safe technology, relatively insensitive to





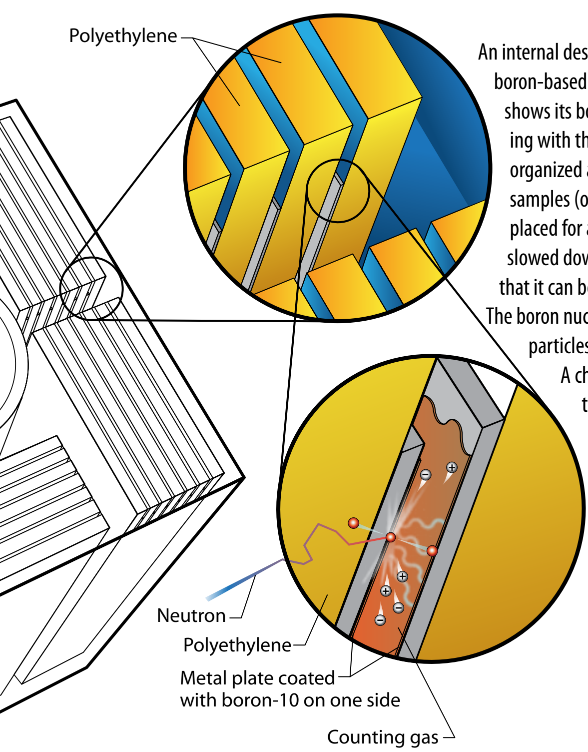
Inside Los Alamos's new boron-based high-level neutron coincidence counter.

CREDIT: Carlos Rael/LANL

gamma rays, and provide stable and reliable performance. Those currently in use have been in operation for decades with minimal maintenance required." Ideally, a replacement system should have all these benefits too.

Taking into account the low-energy neutron interaction properties needed, only two helium-3 alternatives that more or less meet these functionality requirements have percolated to the surface for consideration: boron-10 and lithium-6, in a variety of arrangements. They can be made into gases, liquids, or solids. They can be made into gas counters (like the helium-3 tubes) or light-emitting detectors called scintillators, and each of these can be set up in a number of different geometries (tubes, plates, rods, etc.). The question is, which of these isotopes, in which phase, using which detection technology, and packaged in which geometric arrangement would provide the optimal replacement for helium-based gas counters?

Los Alamos has multiple simultaneous research programs underway to answer this question. While their colleagues down the hall pursue scintillators combined with lithium for neutron detection, Henzlova and Menlove pursue a boron-based gas-counter system that made it to a full-scale safeguards counter and is now, thankfully, ready for serious consideration as a bona fide replacement after all these years—no, make that decades—of research. Later this year, their detector will undergo a field trial using a range of realistic nuclear materials to be measured under real-life conditions. It will be evaluated alongside other prototype technologies from teams around the world at a meeting in Italy to see which, if any, proves viable for routine safeguards use—roughly the equivalent of advancing to human trials in a new drug study.



An internal design schematic for Los Alamos's boron-based neutron coincidence counter shows its boron-coated metal plates alternating with thin counting-gas chambers and organized around a central cavity where samples (of plutonium, for example) are placed for analysis. An incoming neutron is slowed down by a polyethylene moderator so that it can be absorbed by a boron-10 nucleus. The boron nucleus then splits, sending charged particles flying in opposite directions. A charged particle streaming through the chamber's counting gas ionizes some of the gas, creating more charges to be detected by the system's electronics.

Helium-3 is used in extreme-low-temperature cryogenics, among other scientific contexts. For instance, helium can be used to cool superconducting magnets at the world's most powerful particle accelerator, the Large Hadron Collider (LHC), to 1.9 degrees above absolute zero, and the helium-3 isotope allows components for some experiments to get even colder, reaching a small fraction of a degree. For such ultra-cold applications, there is no substitute for helium-3. Shown here: the cryogenics system for the LHC superconducting magnet test facility.

CREDIT: Laurent Guiraud/CERN

Everything in moderation

When a neutron is absorbed by the nucleus of a helium-3 atom in a detection tube, the nucleus splits into a proton and a tritium nucleus. (A nucleus of helium-3 contains two protons and one neutron; tritium, being hydrogen-3, is the other way around with one proton and two neutrons.) Both the proton and the tritium are electrically charged at this point, and as they speed through the surrounding gas, they strip electrons from the gas's atoms, creating an ionization streak comprised of free electrons and positively charged ions. An applied voltage set up within the tube drives these charges toward oppositely charged electrical terminals, where their arrival generates a measurable electrical signal in an external circuit.

Boron-10 works similarly. A colliding neutron fractures the boron-10 nucleus into two smaller, charged nuclei, helium-4 and lithium-7, once again creating an ionization trail through a gas to produce an electrical signal. In both helium and boron detectors, a thick layer of polyethylene surrounds the detection tubes to act as a moderator, dramatically slowing down the neutrons to improve the likelihood they will be absorbed by the helium-3 or boron-10 nuclei. And in both, the moderator also serves as a sort of neutron cage to prevent neutrons from escaping undetected, increasing their chances of scattering back into the detection volume. However, boron-10 doesn't undergo its reaction as readily as helium-3; it absorbs neutrons only about 70 percent as often. And therein lies the greatest challenge: feasible alternative materials are intrinsically inferior to helium-3 for the purpose of neutron detection.

But challenge is not impossibility. Henzlova explains that there are design factors that have the potential to compensate for boron's shortcomings—in particular, the type and number of detection modules (e.g., gas tubes or plates), their geometric positioning, and the manner of coordinating the moderator with the boron.

Henzlova and Menlove focused on three types of boron-based detection modules, each with a different internal organization and each manufactured by a different supplier. They created a test procedure to assess their performance and optimized them with additional moderating material. This took some doing because nuclear safeguards applications impose significant requirements upon the detectors. The detectors must possess extreme gamma-ray insensitivity, demonstrated ease of operation for inspectors in the field, and, in some cases, the ability to perform measurements unattended for months or years at a time.

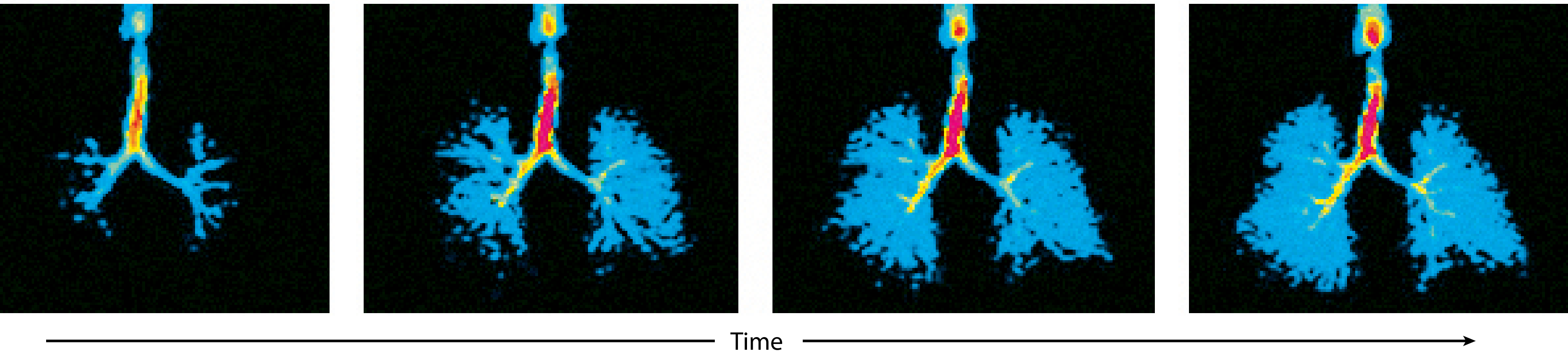
Ultimately, a winner was identified. Their chosen design turned out to use a detection module containing a flat stack of boron-coated metal plates sandwiching thin chambers filled with "counting gas," wherein neutron-absorption ionization trails trigger electrical measurements. (In existing detectors, helium-3 is both the neutron absorber and the counting gas, but boron-10 is only the former. Its detection module employs a similarly inert counting gas, comprised primarily of argon.)

"The large number of plates amounts to a large surface area for the boron," Henzlova says. "Unlike gas tubes, in which helium fills the entire tube volume, boron coatings occupy only a thin surface. But solids are denser than gases, so with enough surface area—and with optimal coupling between the moderator and the boron—we can compete with gas-tube detectors currently in use."

The next step was to optimize the full-scale design based on the selected detection module. To optimize a single, cylindrical helium-3 gas tube, for example, one might start by deciding how thick the surrounding polyethylene moderator should be to send the most neutrons into the gas tube with the right energy range to be detected (that is, the right speed). A typical neutron from a sample of plutonium, say, would have to down-scatter among the atoms of the moderator to effect more than a million-fold decrease in energy for optimal detection. It's possible to calculate how thick the moderator should be to obtain that million-fold decrease, but that will only take care of the front side—the side facing the sample neutron source. The other sides must be engineered to optimally redirect neutrons that missed the tube (or passed through it undetected) back into it. And that's just for one tube. A more sophisticated design typically involves tens of tubes arranged in a ring pattern around a sample container, all jointly embedded in one or more optimally shaped polyethylene blocks.

To make the optimization process more tractable, Henzlova and Menlove developed a computer-based geometric simulation with which they could rapidly test different designs and calculate the probable neutron detection rate for each. Their ultimate goal was to obtain a detector with physical features and performance characteristics comparable to an existing safeguards standard based on helium-3. When they identified that optimal design, they created engineering schematics and physically built the device to test its actual performance.

All this test, design, and optimization work paid off. Indeed, in their field-test device, which is only marginally larger than the helium-based detector currently used for IAEA inspections, Henzlova and Menlove, for the first time, achieved a 7 percent *greater* neutron detection efficiency than



Helium-3 is used to obtain real-time medical imagery of gas inhalation into the lungs to help diagnose lung diseases at an early stage and thereby preserve quality of life for the patient. (Don't worry: this time sequence of images indicates healthy lungs.) Los Alamos research into replacement technology for helium-3-based nuclear detectors could help to relieve the demand for the isotope, helping to save it for important specialty applications like this one.

CREDIT: Jim Wild/University of Sheffield that of the helium-3 system. And because their device relies on a particular method of integrating prefabricated detection modules, even greater efficiencies could be obtained by working with the modules' manufacturer to adjust their design for better functionality within the overall device.

Seeing double

The helium-3 detector that served as a benchmark, the high-level neutron coincidence counter, was originally developed at Los Alamos by Menlove in 1983. And like its potential successor, it is more than a simple neutron detector. In addition to counting incoming neutrons, it also identifies and counts coincident neutrons—two neutrons produced at the same time by the same source. Such neutrons are produced by fission reactions and are a telltale sign that nuclear materials are present. Each fission reaction releases multiple neutrons, and this multiplicity induces a distinctive signal in a neutron coincidence counter. For detailed inspection work in nuclear facilities worldwide (bulk plutonium handling facilities, nuclear material processing facilities, and storage sites), neutron coincidence counters are routinely used.

The trouble is, even though multiple neutrons are emitted by the nuclear material at the same time, they may not reach the helium or boron at the same time after bouncing around inside the polyethylene moderator for randomly different amounts of time. Even if two (or more) neutrons from the same fission are both detected, they won't register a coincidence unless the detections occur at nearly the same time. For that reason, neutron coincidence counters must be specifically designed for both high neutron detection efficiency and accurate assessment of fission-produced coincident neutrons.

To take into account the close timing needed to detect coincident neutrons, scientists in the business have created a composite "figure of merit"—a calculated numerical score that blends the efficiency and timing characteristics of a coincidence counter into an overall measure of its performance. Relative to the benchmark helium-3 detectors in use now, the new Los Alamos boron-10 detector, with its slightly higher neutron-detection efficiency, has somewhat more difficulty with coincident timing. Its overall figure of merit, based on physical hardware tests, is 81 percent that of the helium-3 system, although the simulations suggest that adjustments to the design of the prefabricated boron detector modules within the integrated system could bring the figure of merit up to parity, or even slightly above.

"It remains to be seen if our coincidence counter is good enough for international safeguards use," Henzlova says, referring to the meeting in Italy later this year. "But the initial tests at Los Alamos were promising, and the simulations suggest there is room for further improvement."

Daniela Henzlova and Howard Menlove celebrate their neutron detectors, new and old, with a helium-4 balloon. The helium-3-based high-level neutron coincidence counter (cylindrical, left), invented by Menlove in 1983, may soon be replaced in nuclear safeguards applications by their new boron-10-based coincidence counter (right).

Menlove is optimistic as well. "I've been working on alternative detectors for a long time, and this system is the first one I've seen that performs comparably to the helium-3 counter," he says. Indeed, because the system is so closely patterned after the helium system's design—effectively swapping out helium modules for boron ones, coupling them with the same moderator, and adding compact electronics—there's no reason to expect any problems with performance, manufacturability, safety, or the like. "The only real unknown at this point is cost," he adds. "We've only built prototypes, so we can't know yet what the eventual production and maintenance costs will be. But there's no reason to expect them to be prohibitive."

Possible cost surprises aside, the new system has the potential to contribute to the reduction of global demand for helium-3, and none too soon. With existing reserves shrinking, only a major cut in demand, or an equally major boon in supply, can stop the bleeding. And while several alternative sources of helium-3 are being considered, none is expected to be feasible in the near term. Staving off the immediate shortage, therefore, means reducing the demand with a viable, high-performance, non-helium coincidence counter. So it's probably a good thing Henzlova and Menlove just built one.

—Craig Tyler